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1. Introduction

The FCC has announced in its Docket No. 99-168 [1] that the current TV-UHF channels 60, 61, 62 and 65, 66 and 67 would become available for potential spectrum auctioning for commercial purposes after January 1, 2001. This spectrum would become available in the year 2006 as part of the transition to digital television, although full power UHF-TV licensees will be permitted to continue operations protected from interference until the deadline for conversion to digital television (DTV). The two actual frequency ranges are 746-764 MHz and 776-794 MHz, with the median frequency being 770 MHz.

The Commission sought comments on its proposals to adopt service rules to permit new services such as a variety of wireless and broadcasting services. In its Response to the Notice of Proposed Rulemaking [2], CEMA indicated that this spectrum holds greatest promise in the US for a new broadcast service to provide free, high-quality multichannel digital audio, information and high capacity data services to mobile receivers. CEMA claimed that there is a significant gap in providing new digital broadcast services to the public, especially for mobile reception. This new terrestrial Mobile Multimedia Broadcast Service (MMBS) would bring features currently popular in home entertainment and information products, such as multichannel audio, to the mobile environment.

CEMA urged the FCC to dedicate 36 MHz of radio frequency bandwidth to MMBS, and to adopt the specific technical system to use in view of realizing the full benefits of MMBS for the public and maximize potential spectrum auction revenues. CEMA encourages the Commission to form and empower a government/industry Advisory Committee to develop these requirements further, to assess, evaluate and integrate the appropriate available technologies meeting well-defined criteria, and to recommend a single MMBS standard for Commission adoption.

In its filing, CEMA presented an initial "concept design" that described the capabilities of MMBS. It also indicated that it would hold a "Discovery Group Meeting" to explore the opportunities of such a new service and seek the interest of the various industry segments in such a new service. The present report was commissioned by CEMA in the context of this "Discovery Group Meeting", to develop a system concept design and explore the technical alternatives available in devising such a new MMBS system. The findings are to be presented during this "Discovery Group Meeting" as an initial step in the discussion of the characteristics and the feasibility of such a new service.

2. MMBS service concept

2.1 Basic service objectives

2.1.1 Multichannel sound

In order to be up-to-date with the type of audio service that DTV and Digital Versatile Disc (DVD) are to provide to the public, this new Mobile Multimedia Broadcast Service (MMBS) is intended to carry very high quality multichannel audio and various levels of lower quality audio reproduction such as stereo, mono and speech, depending on the programming that is broadcast. Newer versions of source coding technologies (*e.g.*, Dolby Digital, Lucent PAC, and MPEG-AAC) promise efficient coding with CD or higher audio quality and are adaptable for multichannel audio service.

2.1.2 Scalability

Scalability of the various audio services for rendition with different types of receivers should be an integral part of the system. For example, the MMBS transmission could be received on a top-of-the-line receiver that provides full multichannel audio and data service functionality. Similarly, more modest receivers could be stereophonic or even monophonic and employ more aggressive compression schemes for subsequent storage and retrieval of audio material. Any type of receivers falling between these two extremes should be accommodated in order to allow the consumers to invest at their own pace in a new receiver and in the new service offerings.

2.1.3 Extensive data services

MMBS, with its potentially large capacity (64 kbit/s and beyond compared to the 1.2 kbit/s of RBDS and 16 kbit/s from high-speed FM Subcarrier broadcast systems) could bring to the mobile user access to a large variety of data services of typically two categories:

1. program related data services which are to accompany the main audio program and augment it with complementary information such as:
   - station identification;
   - song title, artist, and information on recordings;
   - electronic program guide;
   - list of related stations for re-tuning when leaving the present coverage area;
   - list of stations by type of programming (news, sport, pop, easy listening music, etc.);
   - scrolling text related to current radio program (e.g., last artist interview);
   - slide show to be displayed on small receiver display related to the current broadcast, and to what is happening in the studio (e.g., live pictures of the disk jockey).
2. non-program related data services:
   - emergency alert messages;
   - severe weather warnings;
   - news headlines;
   - financial and stock market news;
   - personalized electronic newspaper;
   - sports results;
   - Intelligent Transportation Systems (ITS) information, such as:
     - safety messages and road condition;
     - navigation information and route guidance;
     - local traffic information;
     - up-to-date local car parking availability;
     - information for tourists (hotel availability, restaurants, etc.);
     - local bus, train, airline timetables;
   - local weather information;
   - environmental information (e.g., air quality);
   - local event information (concerts, exhibitions, etc.);
   - subscription or pay-per-listen services (e.g., special event broadcasts, electronic yellow pages, houses and cars for sale, stock market quotations, computer games, software updates, etc.).

A host of services that are time and location sensitive could be delivered to the mobile users through the MMBS receiver. It is anticipated that MMBS receivers will be able to show different levels of services such as text on scrolling alphanumeric displays, pictures and HTML type material on small color displays, and even advanced data services through wireless interfaces (e.g., infrared) between MMBS receivers and laptop computers in the car. In this latter case, display and data storage constraints would no longer exist.

2.1.4 Dynamically re-assignable

The transmission capacity assigned to each audio and data service should be dynamically re-assignable to allow optimization of the channel capacity at any time, according to the program being broadcast and the current service offerings and requirements. The receiver would be capable of tracking these changes in a way that is transparent to the listener. The data capacity can also be dynamically changed depending on the needs of the particular services being offered.

2.1.5 Service tagging information

Due to the high capacity of MMBS, the various services carried in the channel will need to be identified by electronic tags for proper linking at the receiver. The use of existing protocols, as well as extensions thereof, will be preferable to maximize commonality with other broadcast systems. As an example, the RBDS tagging structure should be used: AF (alternative frequencies list), M/S (music/speech switch), PI (program identification), PTY (program type), PTYN (program type name), TA (traffic announcement identification), TDC (transparent data channels), TMC (traffic message channel), and TP (traffic program identification).

2.2 Basic performance objectives

2.2.1 Intended type of reception

Considering the current importance of mobility in new electronic services, MMBS is to be designed primarily for mobile reception although house receivers may also develop to be a sizable part of the market. Mobile reception is the most demanding environment for communication services and represents a clear technical challenge because of the time varying multipath conditions produced by a moving car. Car receiver implementations will typically use antennas located at 1.5 m above the ground with omni-directional receive patterns in the horizontal plane, to allow for changing car directions without a need for complex tracking antenna. Reception will suffer severe multipath conditions caused by signal echoes in the receiver surroundings and Doppler spread caused by the displacement of the vehicle.

2.2.2 Service availability

It is expected that, due to the fact that digital systems are known for their abrupt transition to failure and that, as part of the MMBS signal a plethora of data services requiring reliable reception will exist, the service availability will need to be much higher than what has been assumed so far in planning TV and FM services. Availability in the range of 90%-99% will likely be required. In order to secure such high availability and still use reasonable power and preserve spectrum, new means of service implementation will need to be considered (see section 3.1.2).

2.2.3 Extent of coverage

It is expected that the MMBS station coverage will be similar to that of typical UHF-TV stations, that is, 'wider urban coverage'. In the UHF band, the coverage is generally limited by the RF horizon or terrain blockage. For a 300 m transmit antenna height, the coverage radius is about 88 km (55 miles) for a relatively flat terrain area. Increasing the transmission power will generally not result in much coverage area increase, but it will definitely improve the location availability within the coverage area. For instance, to increase the location availability from 50% to 90%, 7 dB more transmission power is required (assuming $\sigma = 5.5$ dB). On the other hand, in the UHF band, increasing the transmission tower height will almost certainly result in an increase of the coverage radius. However, it will also increase the distance for which the same channel frequency can be reused.

An alternative to this conventional means of covering an area exists for some specific digital modulation systems with appropriate characteristics. Using on-channel repeaters as described in section 3.1.2, a broadcaster may start with a relatively small transmission installation, covering the city core which corresponds to a portion of his licensed coverage area. Progressively, the key highways would be covered and later the coverage would be extended to the suburban areas according to the local population density to maximize the revenue in a timely fashion. The progressive implementation of on-channel repeaters would allow the broadcaster to pace the development of his coverage according to his resources, the density of the population to be covered and the market.

2.3 Return channel for interactivity

MMBS has the potential of becoming a very flexible service, and intelligent receivers, along with sizeable local storage capacity, can bring an extensive level of pseudo-interaction to the user. Aside from the data bases of information with which the user would be able to interact, it is expected that some level of true interaction will also be needed for, as an example, ordering tickets for events that are announced as part of the service. Interactive multimedia services are unlikely to develop as fully for the mobile market as those services available on desktop computers through Internet Service Providers, for the simple reason that such extensive interactivity will usually not be practically possible in the mobile environment. Nevertheless, a certain level of true interactivity should be provided as part of MMBS.

Because of the totally different network topology and transmission system requirements between a broadcast infrastructure for mobile reception and a two-way radio-telephone service, and because of the clear asymmetry between the downlink and the return link capacities, it would be unwise to model a MMBS service on a truly bi-directional communication service. The best approach would seem to be a coupling of a unidirectional broadcast service with an existing radio-telephone service. The amount of information to be transmitted on the return channel is expected to be much smaller than in the broadcast channel and would be best accommodated by existing cellular telephone connections.

Various systems could be coupled to the MMBS receiver to provide a transparent return channel such as the digital PCS services D-AMPS, GSM-1900 or CDMA which are based on a demand access scheme, or a packet based system such as the Ericsson Mobitex system operated by Bell South in the US, which would allow the MMBS receiver to be always on standby and send data packets when required.

Extensive work is being done in Europe on a similar service through the MEMO project to bridge the Eureka-147 DAB system with the GSM radio telephone service for interactive multimedia services over DAB [3]. The investigation of such coupling is beyond the scope of this report and will not be treated further.

3. Transmission channel

3.1 Signal strength and reception noise considerations

3.1.1 Propagation at 770 MHz

Propagation in the upper UHF band suffers from a limited amount of diffraction around objects and terrain features [4]. This range of frequencies was identified in [4] as being close to the optimum for terrestrial and satellite sound broadcasting, considering the better terrestrial propagation towards lower frequencies and also the possibility of covering continental USA from satellite with still a reasonable size transmit antenna. In the case of a terrestrial only service, lower frequencies would bring even better propagation conditions. The use of such relatively high frequencies results in a reduced coverage radius, determined by the transmitter RF horizon which is primarily a function of the antenna height as explained in section 2.2.3. Trying to extend the coverage by conventional means beyond the RF horizon or behind obstructions such as mountains, hills and buildings leads quickly to very high transmit power. The same basic propagation models as used for planning TV-UHF coverage can be used for MMBS.

3.1.2 Improved coverage through the use on-channel repeaters

The difficulty in trying to reach beyond the RF horizon in the case of UHF-TV stations has been well understood in the context of duplication of the coverage of current analog VHF-TV stations by new UHF-DTV stations, resulting in very high power requirements. In the case of this new MMBS service, which is dedicated to mobile reception and is expected to require a rather high service availability (section 2.2.2), trying to rely on a single high power transmitter would likely result in an excessive transmit power requirement. Another means of achieving the coverage has to be relied upon. The use of on-channel repeaters seems to be the only way by which a high level of service availability can be secured over the entire service area.

This new option stems from the use of a new type of modulation for MMBS that should be able to take full advantage of a multipath reception environment created by signal reflections from nearby buildings as well as active echoes from multiple on-channel repeaters (see section 4.2.7). These on-channel repeaters can be used to extend the coverage beyond the RF horizon and fill the gaps in the coverage areas resulting from shadowing, yet still using only the one frequency assigned to the station. The use of on-channel repeaters can also be seen as building transmitter site diversity, which results in a more reliable coverage from the presence of a network gain produced by the multiple signal level statistics at the receiver.

The use of such repeaters will also allow progressive extension of the coverage as well as gradual improvement of the service availability within the service area, without the need for more spectrum. The broadcasters will be able to improve their service at their own pace without a need for regulatory change to their license, as long as these improvements are within the bounds of the licensed area. The other advantage of using these on-channel repeaters is that interference outside the service area can be better controlled than in the case of a high-power single transmitter. The field strength drop-off at the edge of the coverage area can happen over a shorter distance.

As an example, a broadcaster who has been granted a license to cover a given service area (not necessarily circular) may be able to start with a central transmit installation, producing a reasonable but limited coverage. With time, the organization could extend the coverage by installing new on-channel coverage extenders, as well as improve the service availability inside its service area by adding on-channel gap-fillers to cover the shadowed spots. The pace at which this could be done would depend on the business case. As long as the broadcaster does not produce more interference beyond the edge of its declared coverage area than initially established in its licensing process, it would be reasonable to assume that there should be minimal regulatory hurdles. (Regulatory aspects are beyond the scope of this work and are only mentioned here as an indication of areas where there could be a need for refinement because of the added flexibility brought by the use of on-channel repeaters.)

There are various ways to feed these on-channel repeaters. The simplest feed mechanism is through RF pick-up for which no distribution infrastructure is necessary. One has to rely on the isolation between the directional receive antenna aimed at the main transmitter, and the omni-directional or sectoral transmit antenna, to be able to amplify the signal sufficiently to broadcast enough power to secure the wanted coverage extension. Local obstructions can be taken advantage of in this case [5]. The on-channel re-transmitters can also be fed by a synchronous network, giving more flexibility in locating the transmitters as will be explained in section 4.2.7. However, in this case, a distribution infrastructure such as microwave or optical fiber would be needed.

3.1.3 Effective antenna noise temperature

Industrial noise, also called man-made noise is a major factor limiting the sensitivity of receivers at low frequencies. Fortunately, its level decreases with an increase in frequency at a typical rate of 28 dB/decade, reaching a negligible level in the low microwave range. According to the ITU-R Reports 258 and 670, the typical level of industrial noise in the range of 740-800 MHz is equivalent to some 51° Kelvin. Beyond industrial noise, thermal noise from the surroundings as well as sky noise due to oxygen and water vapor contribute to the antenna noise temperature. Taking into account the directivity of the receiving antenna (i.e., 25% of its pattern sees ground structures versus 75% looking at the sky), the total effective antenna noise temperature is expected to reach some 146°K.

The level of antenna noise is used in establishing the performance of the RF front-end of the receiver. Even if the quality of the receiver front-end was to be improved dramatically, this antenna noise level sets a minimum level achievable, beyond which a point of diminishing return would be reached in trying to improve the low-noise amplifier.

3.1.4 Receiver noise figure

Lately, technology has proven to be capable of producing receivers with very low noise figures consistently and in high volume. This development came from the satellite reception side (DBS), for which every dB improvement against thermal noise is very important in terms of reducing the satellite transmit power. Noise figures of less than 1 dB are quite current in the 4 GHz band. In principle, even lower noise figures should be possible at a lower frequency such as 770 MHz. An additional constraint, not present in the case of satellite reception, tends to limit the noise performance of the receivers. This is due to the requirement to secure a wide dynamic range for the receivers since they will be faced with trying to receive low power distant signals in presence of high power signals from nearby transmitters (the near-far reception requirement). At such high frequencies, this is somewhat mitigated by the fact that the vertical pattern of the transmit antennas can be more easily controlled, resulting in lower sidelobe levels towards the ground. In practical situations, there does not seem to be a need to secure a saturation level of more than −15 dBm at the input of the receiver unless other services such as UHF-DTV produce very high field strength towards the ground around the transmit antenna. As part of the MMBS system design and specification, such a control of the vertical transmit antenna pattern could be considered. In such a case, a more reasonable trade-off between receiver RF dynamic range and the sensitivity of the RF front-end could be found.

In the case of VHF and UHF-TV reception, this trade-off has been more conservative and favors dynamic range with a rather poor noise performance. This is due to the fact that, at lower frequencies, especially at VHF, the presence of high level external noise limits the effectiveness of bringing the receiver noise figure to very low values.

Since the frequency range of interest for this MMBS is in the upper UHF band, and digital modulation can be designed to be more immune to industrial noise, there is a clear advantage in trying to improve the receiver noise figure to the extent possible while still preserving a reasonable dynamic range. The technology developed for cellular radio and PCS should be used advantageously, since the requirements on the dynamic range will most likely be less demanding in the case of this unidirectional broadcast service. Although a noise figure of 5 dB was assumed for DTV in the UHF range, 3 dB is believed to be more appropriate for this new service and will be used as an illustrative value in this exercise.

3.1.5 Receiver figure of merit

The receiver figure of merit is calculated based on different assumptions made on the receiver parameters. Since the receive antenna is to be mounted on a car, no directivity can be assumed (unless a tracking antenna is to be used, resulting in a much more complex installation). A limited gain of 0 dBi is therefore assumed for a typical antenna. An antenna coupling loss as well as a pre-selective filter loss of 2 dB is assumed. This conservative value, mainly representing the filter loss, is due to the need to reject the neighboring high power UHF TV signals by a rather sharp pre-selective filter.

The calculation of the receiver figure of merit is based on the following equation:

$$G/T = \frac{\alpha G_r}{\left(\alpha T_a + (1-\alpha)T_o + (n-1)T_o\right)}$$

where:

α: the total coupling losses at the input of the receiver (including any pre-selection filter) (= 2 dB)

G_r: the effective gain of the antenna relative to an isotropic source (= 0 dBi)

T_a: the effective temperature of the antenna, considering the antenna directivity toward the ground (290°K) and toward the sky (90°K), and including industrial noise at the operating frequency (51°K) (= 146°K)

T_0: the reference temperature (= 290°K)

n: the overall noise figure of the receiver (= 3 dB)

This results in:

$$G/T = -28.9 \text{ dB } (K^{-1})$$

3.2 Channel multipath considerations

Communication systems having to operate in a mobile environment are faced with a high level of RF signal echoes, produced by signals bouncing of various surfaces surrounding the receiver and resulting in multipath conditions at the receiver. In fact, RF reflections from terrain features and ground structures seem to be omnipresent at most frequencies (see section 3.2.2).

Multipath is less of a problem for systems using very directional receiving antennas, such as point-to-point systems, since the antenna discriminates among the various received RF paths. This is also true, although to a lesser extent, for TV reception with roof-top mounted Yagi-type antennas. This advantage is lost when one tries to receive TV signals using "rabbit-ear" indoor antennas with the well known appearance of ghosting on the picture. In the case of mobile reception, which typically requires omni-directional transmit and receive antennas, little path discrimination can be offered by the antennas and the system has to perform in very difficult multipath environments.

A multipath channel is rather difficult to deal with, especially when the direct path is not present (frequently leading to Rayleigh fading). It typically produces frequency selective fading within the transmitted channel, reducing the received signal power and producing major signal distortion, which translates into inter-symbol interference (ISI) in the case of digital transmission. In the case of mobile reception, this signal distortion changes in time at a pace that is related to the speed of the vehicle. This creates a spreading of the signal in the frequency domain. This phenomenon is known as the

Doppler spread of the channel. Tracking this distortion at the receiver in order to compensate for it becomes rapidly horrendous. The channel signature can change completely in relative phase among the various echoes within a signal wavelength. At 770 MHz, the wavelength is 43.3 cm. For a vehicle moving at 100 km/h, this represents a Doppler variation of some 71 Hz. This represents the rate at which a channel equalizer would have to track the channel variations.

Although enormous effort has been applied at solving these problems for the mobile radio-telephone services [6], a new look at the methods to provide reliable transmission for digital broadcast services in a mobile environment is needed in order to take advantage of the simpler unidirectional nature of broadcast services.

3.2.1 Multipath model

An extensive amount of work has been done to characterize the multipath, which occurs in the UHF range. The main reference is the work done in Europe as part of the development of the GSM mobile radio system. This resulted in the following four mobile channel models, each representative of a different geographical environment, developed by the COST 207 committee on Digital Land Mobile Radio Communications [7]:

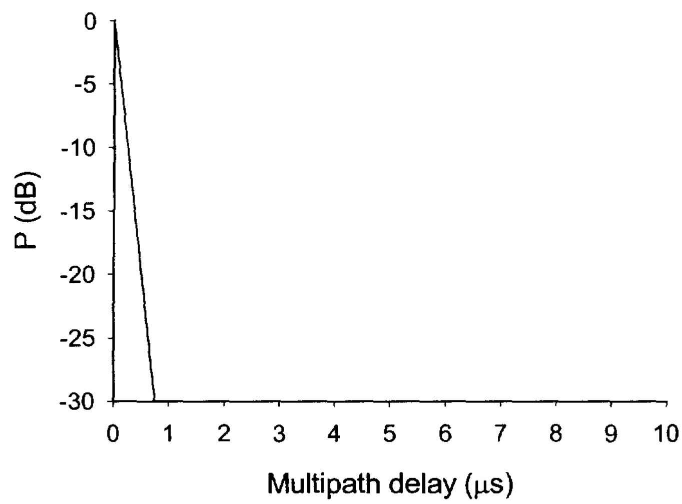

Figure 1: Multipath power delay profile for rural areas

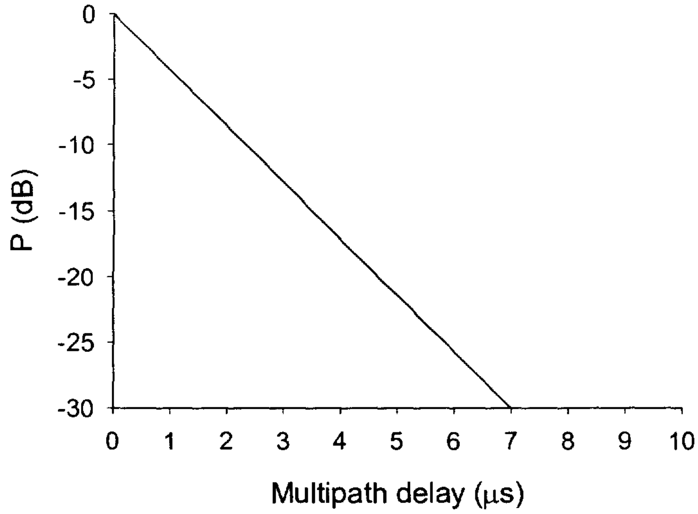

Figure 2: Multipath power delay profile for urban areas

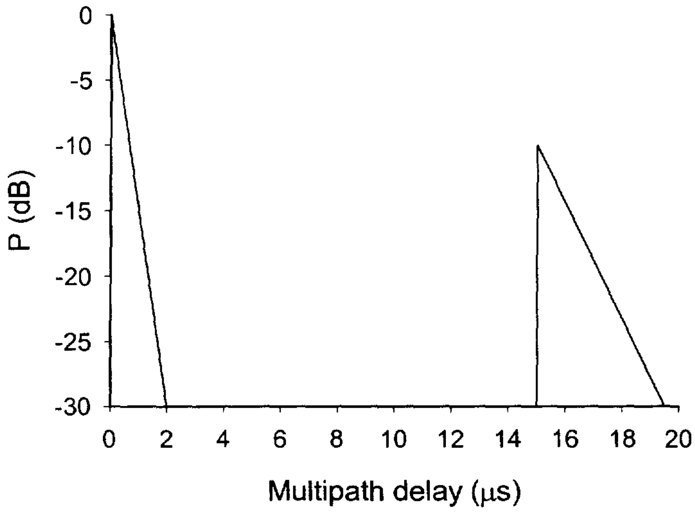

Figure 3: Multipath power delay profile for typical hilly terrain

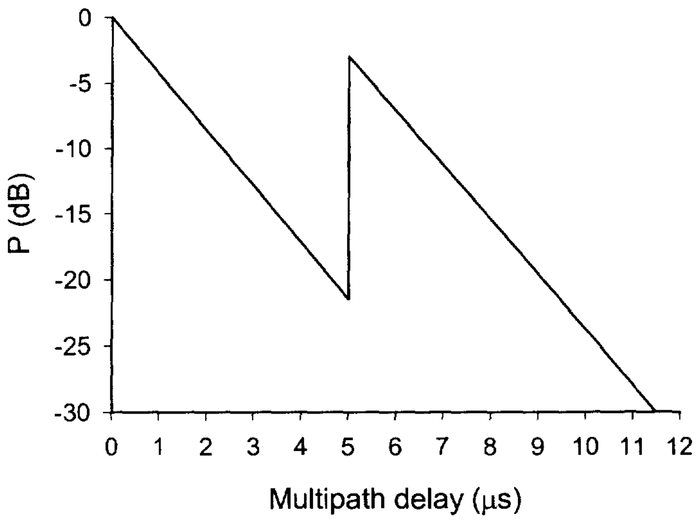

Figure 4: Multipath power delay profile for bad case hilly terrain

Extensive field measurements were carried out in the US as part of the EIA/NRSC DAR effort in the 1992-1995 period [8] as well as in Canada, conducted by the CRC during the same time period [9]. All these results tended to confirm the validity of the COST 207 model, and similar models were used to derive the multipath parameters used to simulate typical channels in the EIA/NRSC DAR system tests [8]. Usually simulating a multipath channel is done using a number of discrete signal paths according to the above power delay profiles. This is a good approximation of the real phenomenon appearing in the field and corresponds to a finite set of 'specular' reflections. In reality, the transmission channel produces 'specular' as well as 'diffused' echoes and the total effect is a composite of these multiple echoes.

3.2.2 Multipath versus frequency

The multipath characteristics of the spectrum in the 800-900 MHz region have been studied quite thoroughly, due to the extensive deployment of mobile radio-telephone systems in this band. The COST 207 [7] recommendations on channel characterization were derived from studies in that region of the spectrum. During the EIA-DAR laboratory tests, the question arose whether channel models similar to those used in COST 207 would be applicable to VHF and L-Band frequencies.

There is unquestionably a significant frequency dependence in terms of propagation losses – the attenuation resulting from diffraction around objects or penetration through them almost invariably increases with frequency. Multipath, however, is a different matter. One good indicator of the amount of multipath present on a channel is the "delay spread" parameter. One authority (Lee [6]) concludes that "the data available show that the delay spread is independent of the operating frequency at frequencies above 30 MHz". The explanation for this is as follows: as the wavelength increases, the energy scattered off a given object tends to decrease (more absorption and diffraction), which would decrease the amplitude of the multipath reflections. On the other hand, path loss decreases with increasing wavelength, and these two effects tend to balance each other, making delay spread roughly independent of frequency.

A similar conclusion is reached by Springer [10], who states that "there is support for the proposition that most of the important statistical parameters are relatively constant across the VHF and UHF bands". This proposition is also supported by measurements performed by CRC over the past six years. An extensive program of L-Band measurements in different parts of Canada showed that the multipath characteristics in this band were substantially similar to those in the COST 207 models [9,7]. In addition, measurements were performed in Montreal at VHF (85 MHz) and compared with those at the same receiving locations at L-Band (using the same transmission tower), and again considerable similarity in channel characteristics was found. A report on the results tabled at one of the EIA DAR Subcommittee meetings [11] concludes: "*Although differing considerably in detail in most cases, as one would expect, we find that the VHF and 1.5 GHz broadcast-to-mobile channels have the same basic characteristics. Both frequently exhibit characteristics which can be well represented by Rayleigh models [i.e., those used in COST 207, and the frequency of occurrence increases with the complexity of the environment, which is certainly no surprise. Perhaps more surprising is the fact that the predominant sources of multipath appear to often be the same in both bands, judging from the similarity of the scatter plots... the results to date support the thesis that multipath effects are relatively frequency-independent over a wide range in the VHF/UHF bands, and that Rayleigh channel models are a good representation of "real world" conditions in complex environments.*"

3.2.3 Effect of echoes with large excess delay

Long-delay echoes are produced by the RF signal reflecting from large and distant structures such as neighboring mountains. With light propagating at 300 m/μsec, an echo with a 30 μsec excess delay results from an RF signal having gone through a 9 km longer RF path than the direct path. Because of the extra spreading loss and partial absorption of energy by the reflecting surface, this long echo is usually received at much lower power than the direct path. A large body of field measurements exists to show that echoes beyond about 30 μsec are usually negligible. This is fortunate because they are the ones most difficult to correct. For example, if the direct path is not available or is attenuated at the reception point, the presence of such a long echo will create inter-symbol interference unless an equalizer operating over such a large equalization window can remove it. A very long guard interval used in the multi-carrier case (see section 4.2.2) could also avoid the ISI.

3.2.4 Effect of echoes with medium excess delay

Echoes with excess delays in the range between about 1 μsec to 20 μsec are the most prominent. They are produced by reflective surfaces in the neighborhood of the receiver or transmitter. They correspond to excess path lengths of 300 m to 6 km. These echoes are clearly the most powerful and the most numerous, due to the probability of finding sizeable reflecting surfaces in this range. Communication systems must compensate for these echoes. For wideband signals, these echoes produce frequency selective fading within the transmission channel and create inter-symbol interference in typical transmissions, as illustrated in Figure 5. This can be corrected by frequency diversity or time equalization, or by discarding the ISI as will be seen in the multi-carrier modulation case (see section 4.2.2).

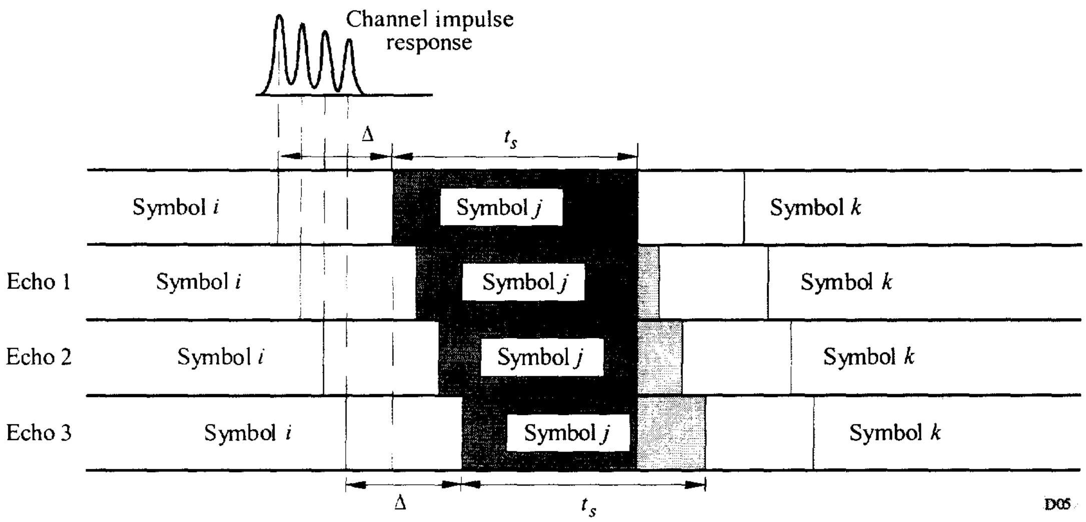

Figure 5: Inter-symbol interference resulting from channel multipath

3.2.5 Effect of echoes with small excess delay

Short echoes are produced by the RF signal being reflected by structures close to the receiver (or the transmitter, but this is less likely). Because of the small excess distance traveled, the reflected signal may approach the power of the direct signal if the nearby surface is very reflective for RF signals. As an example, a 0.3 μsec echo would be produced by a 90m extra length on the reflected path. This could be produced by a reflector located some 45 m from the receiver. These short echoes tend to create flat fading at the receiver, depending on the channel bandwidth. Frequency diversity is also an effective means to counter the effect of short echoes, if sufficient bandwidth is available. If flat fading is experienced over the whole channel bandwidth, then one has to resort to time diversity (in the case of a moving vehicle) or antenna diversity to recover the signal. Fortunately, the occurrence of such short echoes seems to be less than that for echoes with medium excess delay (see section 3.3). This is probably due to the fact that the likelihood of finding large reflecting surfaces closer than 300 m from the receiver is low.

3.3 Channel bandwidth versus frequency selective fading performance

A modulation system that is capable of fully taking advantage of a multipath environment (i.e., operating on the power sum of all echoes) is able to fully correct the effect of frequency selective fading due to multipath. However, in the case of echoes with very small excess delays, which would produce flat fading over the entire transmission channel bandwidth, this modulation system will unfortunately have no means to recover the signal during these fades.

The only means to reduce the occurrence of this defect is to use a wider channel bandwidth, thus limiting the range of short echoes that will bring the system in a flat fading situation. The results of a field measurement program undertaken by the CRC were reported to the ITU-R in 1993 [12]. A wideband pseudo-noise signal was transmitted by a 1.5 GHz high power transmitter over the Ottawa region and was received by a spectrum analyzer with a range of IF filter bandwidths. The statistics of flat fading occurrence were analyzed. Figure 6 summarizes the findings. These results were used to confirm the need for a minimum channel bandwidth to allow adequate frequency diversity to cover for short echoes in a typical channel. The results showed that the channel bandwidth has a major impact on the possible reduction in transmitter power for a same service availability.

The information about the possible reduction in transmit power for a given service availability lies in the difference in decibels between the cumulative distribution curves of the different bandwidths, at specific percentages of service availability. Figure 6 shows that significant reductions in required transmit power can be obtained by increasing the channel bandwidth to avoid flat fading due to close-in echoes. These curves represent a different way of showing the probability of occurrence of these echoes in a way that is readily usable for system design consideration. Each curve can be divided into two sections, the first part being from 100 kHz to a bandwidth value that corresponds to a knee in the curve, the second part being from the knee position to the widest bandwidth measured (5 MHz). The criterion used to consistently locate the knee position is to find the point along the 99% service availability curve that corresponds to 1 dB transmit power increase as compared to the value obtained at 5 MHz.

This method of quantifying the effect of the bandwidth on the required transmit power was applied to different types of reception environments and the results are summarized in Table 1. This table shows the possible reduction in transmit power as the channel bandwidth is increased from 100 kHz to 5 MHz for service availability objectives of 90% and 99%.

Typically, the 90% service availability objective curves show a reduction in required transmit power in the order of 4 dB, from 100 kHz to the knee (1.1 to 1.9 MHz), and a reduction remaining below 0.7 dB from the knee to the 5 MHz bandwidth value whereas this reduction is in the order of 8 dB for 99% service availability.

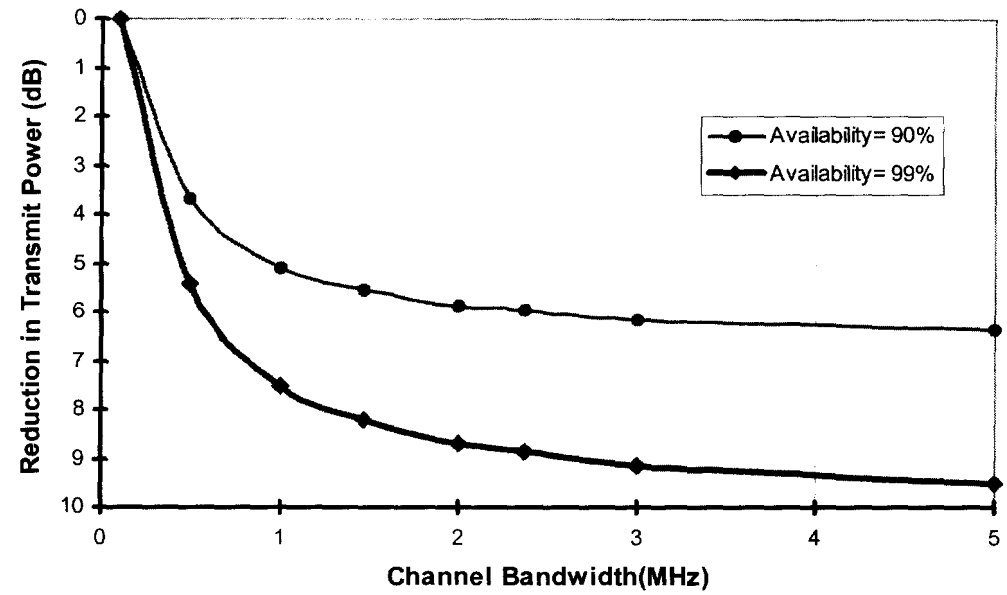

Figure 6: Reduction in required transmit power resulting from a widening of the transmission channel bandwidth (Dense urban, Ottawa)

Type of environment	Knee position MHz	Typical reduction in required transmit power (dB)			
		100kHz-to-knee		Knee-to-5 MHz	
		90%	99%	90%	99%
Dense urban	1.8	5.4	8.6	0.5	1.0
Urban	1.6	4.5	7.0	0.6	1.0
Suburban	1.9	4.1	8.1	0.6	1.0
Rural, forest	1.7	3.7	6.0	0.7	1.0
Rural, open	1.1	1.2	1.8	0.7	1.0

Table 1: Multipath fade margins for service availabilities of 90% and 99%

The appropriate choice for the transmission channel bandwidth is therefore a value around 2 MHz. Below 2 MHz, the multipath fading increases rapidly, while above 2 MHz the improvement in fade margin is generally not very significant. It is recognized that there may be a need to conduct further field measurements to correlate these findings on a wider base, since they address a very fundamental parameter of the MMBS system design.

With the above findings, and due to the fact that the MMBS system should preferably fit in the normal 6 MHz NTSC channel, it is suggested that the MMBS channel bandwidth be 1.5 MHz.

3.4 Artificial multipath conditions created by single-frequency network

When on-channel repeaters are used to extend or improve a coverage area, the typical rules of the COST 207 model no longer apply. The amplitude of the echoes no longer typically decreases monotonically with the excess delay. In fact, the amplitude of these echoes becomes dependent on the location of the receiver relative to the various re-transmitters. Delayed echoes may become more powerful than earlier echoes if the receiver gets closer to the re-transmitters emitting these delayed echoes. This translates into a potential for a large amount of pre-echoes.

Depending upon the distance between these on-channel repeaters, the echoes produced may have very large excess delays, well beyond those typically seen for passive echoes. This creates more demanding conditions at the receiver than a typical multipath environment.

In the multi-transmitter case, different signals can reach the receiver with the same amplitude. The equal power echoes create some especially difficult conditions at the receiver. As an example, the channel tracking algorithm of most time equalizers cannot converge under these conditions. Any receiver which relies on predictive algorithms for tracking channel conditions will not be able to acquire the signal properly, resulting in reception failure even though there is adequate signal power available.

4. Transmission system strawman

4.1 Basic alternatives

4.1.1 Single carrier modulation (SCM) plus equalizer

This is the most common modulation used. For simple modulation state constellations, it has the advantage of optimizing the transmitted signal for non-linear transmitters by minimizing the crest factor; i.e., the difference between the peak power and the average power. By selecting a constant envelope modulation and choosing a channel filter with proper bandwidth roll-off factor, the transmitted signal can achieve an almost constant amplitude, allowing the high power amplifier to operate close to saturation, therefore allowing more efficient operation. This is especially important in satellite transmission, where the satellite power consumption is a prime consideration. It is also important in the case of terrestrial operation, to maximize the HPA efficiency and minimize the need for channel filtering due to reduced spectral re-growth in the channel sidebands.

The main disadvantage of this form of modulation is that reception in a mobile multipath environment requires a very complex channel equalizer in the receiver. In the case of using on-channel repeaters, channel equalization is made even more difficult with the need for a wider equalization window and with the possibility of the channel tracking algorithm not being able to converge as in the case where echoes with typically less than 3 to 6 dB signal amplitude differential are received. Since channel tracking is required at the receiver, coherent demodulation is also used to provide maximum signal sensitivity. Table 2 summarizes the comparative merits of this SCM alternative.

4.1.2 Multi-Carrier Modulation (MCM)

The basic principle for multi-carrier modulation consists of dividing the information to be transmitted into a large number of bit-streams, each having corresponding low bit rates. These low bit rates are then used to modulate each individual carrier. In order to preserve spectrum, these carriers are spaced in such a way that they are all orthogonal to each other. This is done very elegantly by applying an inverse FFT at the transmitter. The specific type of MCM resulting is an orthogonal frequency division multiplex (OFDM) modulation.

The symbol duration on each carrier becomes large and can easily be extended beyond the delay spread of the transmission channel. An added feature of this modulation is the insertion of a guard interval between the useful symbols to absorb most of the energy from the time spreading of the signal by the transmission channel. This offers a great improvement to reception reliability by removing inter-symbol interference (ISI) at the price of a fraction of a dB loss in signal recovery, since the receiver integrates the incoming signal during the useful symbol period rather than the full symbol period. The signal at the beginning of the symbol is repeated at the end to allow recovery on a sliding window over the symbol, since the symbol synchronization will vary depending on the measured impulse response of the channel. The channel throughput is also reduced by the ratio of this guard interval over the full symbol period. The effect of absorption of the ISI during the guard interval is illustrated in Figure 5. In the receiver, any echo shorter than the guard interval will not cause any inter-symbol interference, but rather will contribute positively to the received signal power (see Figure 5).

The OFDM process can also be explained in the frequency domain. In the presence of multipath propagation, some of the carriers are enhanced by constructive signals, while others suffer destructive interference (frequency selective fading). Time and frequency interleaving then need to be applied to allow for a redistribution of the elements of the digital bit stream in time and frequency, so that successive data stream bits are affected by independent fades. In order to recover the bits lost by the faded carrier, channel coding is implemented, so that the reliability of the strong carriers can help to reconstitute the full bit stream. This is achieved in the receiver by a soft decision Viterbi decoder. The use of channel coding on these time and frequency OFDM symbols constitutes the COFDM system [13, 14].

When the receiver is stationary, the diversity in the frequency domain is the only means to ensure successful reception (unless one goes to the extent of using antenna diversity). However, when the receiver is moving, time-interleaving comes into play to improve the situation. For a system using COFDM, multipath propagation is a form of space-diversity and is considered to be a significant advantage, in stark contrast to conventional FM or narrow-band digital systems where multipath propagation can completely destroy a service. Past studies have demonstrated the advantages of COFDM modulation to overcome difficult mobile multipath reception environments.

This special characteristic of the COFDM modulation is taken advantage of by implementing on-channel repeaters, which actually create active echoes to improve the performance at the reception. This results in a further benefit of using COFDM, as higher spectrum and power efficiency is obtained by the use of on-channel re-transmitters, forming single frequency networks to extend the coverage over larger areas. They may also be used to improve the coverage in difficult situations, such as dense city environments, through transmitter site diversity (see section 3.1.2).

For mobile applications, DQPSK modulation is typically used with COFDM to allow differential demodulation at the receiver for a very robust transmission, thereby avoiding any need for carrier recovery and channel prediction at the receiver. One could also use coherent demodulation using pilot carriers to permit proper channel prediction. Although this would allow for some 3 dB improvement in signal sensitivity in an AWGN channel, the improvement would be more like 2 dB in a complex Rayleigh multipath channel, therefore bringing the improvement to less than 2 dB due to the need for channel capacity for the pilot carriers. The other advantage of coherent demodulation would be the reduced impact of the channel Doppler spread on the transmission, therefore allowing higher vehicle speed or the use of a larger guard interval. The gain would be limited, however, since the trade-off possible at 770 MHz is already quite acceptable (see section 4.2.8). The main reason in favor of a differential demodulation is the simplicity of the receiver and the resulting lower power consumption, which is of particular interest in the case of portable receivers.
Due to the use of the inverse FFT in the transmitter, there is an inherently rapid sideband roll-off that aids in reducing adjacent channel interference produced by the high power amplifier at the

transmitter. The same process resulting from the FFT in the receiver allows an improvement in robustness against adjacent channel interference. As long as the A/D converter is kept from being driven into saturation, this intrinsic adjacent channel interference rejection from the FFT improves the adjacent channel rejection capability of the receiver. The merits and drawbacks of MCM and, in particular, COFDM are reviewed in Table 2.

4.1.3 Coded Division Multiplex (CDM)

Spread spectrum techniques are used in various communication systems. In particular, the mobile radio standard IS-95 is based on a direct sequence spread spectrum technique.[15] It has the advantage of using a wider bandwidth (1.25 MHz) than other types of PCS, hence securing better frequency diversity in a multipath environment than narrowband systems. It has some clear advantages in the case of bi-directional communications, since a number of signals can share the same transmit and receive bandwidths based on the use of orthogonal codes as long as the power levels present at the receiver are tightly controlled. In a unidirectional system such as MMBS, these advantages are counterbalanced by its limitations. In order to function properly in a multipath environment, a RAKE receiver needs to be utilized with proper channel prediction algorithms. A similar problem as in the case of the time-domain equalizer may exist when equal amplitude echoes are received. There could also be some ambiguity in echo excess delays when it is beyond the symbol period limiting the flexibility in physically locating on-channel repeaters since the maximum repeater spacing is related to the extent of the time window covered by the RAKE receiver. Also the complexity of the receiver is not negligible, especially in the case of being able to track a complex multipath channel in a fast moving vehicle. The merits and limitations of this technology are summarized in Table 2.

4.2 COFDM solution

As can be seen from Table 2, there is a clear advantage for the MCM approach (COFDM modulation) because a much simpler receiver can secure reliable reception in a multipath environment. As indicated in Table 2, COFDM only requires time synchronization sufficiently good to make sure that most of the energy from the various signal echoes (passive and active) fall within the guard interval. This is depicted in Figure 7. In the case of the two other modulations (and in the case of a coherent QPSK demodulation for COFDM), a complete channel estimation in amplitude, phase and excess delay is needed to be able to recover the signal. Figure 8 depicts the information that is required for full synchronization. In a vehicular situation, this complete channel estimation needs to be updated in real time and may require excessive computational power at the receiver (rate of variation can be up to 71 Hz at 770 MHz for a vehicle moving at 100 km/h). It is clear that MCM (COFDM) is the best modulation to be used for the terrestrial MMBS, especially where on-channel re-transmitters are to be used.

Since the COFDM modulation is found to be the most promising, a closer look at this modulation will be taken using the Eureka-147 DAB system as the prime model since it is the better known, [13, 14, 16] although a number of new systems are expected to use COFDM as well (see sections 10.1, 10.3, 10.4 and 10.7).

4.2.1 Modulation scheme

COFDM is a channel coding and modulation scheme, which was designed specifically for digital broadcasting to portable, vehicular and fixed receivers. It incorporates three key features to combat the time and frequency selectivity of mobile channels.

Parameters	Single-carrier modulation [16]	Eureka-147 DAB multi-carrier modulation [17]	Coded division modulation [18]
Modulation	QPSK-TDM	DQPSK-COFDM	QPSK-CDM
Typical spectrum efficiency	0.86 bit/s/Hz	0.75 bit/s/Hz	0.38 bit/s/Hz
Required Eb/No in AWGN channel (BER=10^{-4})	2.7 dB	7.2 dB	4 dB
Required Eb/No in Rayleigh channel (BER=10^{-4})	Depends on the performance of the time domain equalizer	11.2 dB	Depends on the performance of the RAKE receiver
Advantage of the modulation for non-linear amplification	7.1 dB (TWTA) 6.7 dB (linear HPA) (constant envelope modulation, coherent demodulation)	0 dB (reference point) (multi-carrier modulation, guard interval, differential demodulation)	3.2 dB (coherent demodulation)
Impact of terrestrial repeater on receiver complexity.	Need complex channel estimation and time equalizer before coherent QPSK demodulator.	COFDM requires a partial FFT in the receiver. It was optimized for terrestrial multipath propagation.	Need de-spreading code acquisition and tracking, complex channel estimation and RAKE receiver.
Level of channel estimation required in the receiver (complexity).	Complete channel estimation (amplitude, phase, excess delay) is needed for the operation of the channel equalizer in a multipath environment.	Proper timing of the start of the symbol is needed for the FFT window. Most of the energy from the impulse response of the multipath channel has to be contained within the guard interval.	Complete channel estimation (amplitude, phase, excess delay) is needed for the operation of the RAKE receiver in a multipath environment.
Vehicular reception	Computation complexity increases rapidly with variability of the channel (Doppler spread proportional to vehicle speed and carrier frequency) and extent of equalization window.	Possible trade-of between immunity to Doppler spread (for a given vehicle speed and carrier frequency) and extent of the guard interval in selecting the proper transmission mode.	Computation complexity increases rapidly with variability of the channel (Doppler spread proportional to vehicle speed and carrier frequency) and time window covered by the RAKE receiver.
Use of multiple on-channel repeaters	Possible but creates instability in the equalizer if repeater signals reach the receiver at the same amplitude. Maximum repeater spacing is related to the extent of the equalizer window.	Maximum repeater spacing is related to the extent of the guard interval.	Possible but there could be ambiguity in echo excess delays when it is beyond the symbol period. Maximum repeater spacing is related to the extent of the time window covered by the RAKE receiver.

Table 2: Comparison of the merits of three modulation systems considered for MMBS

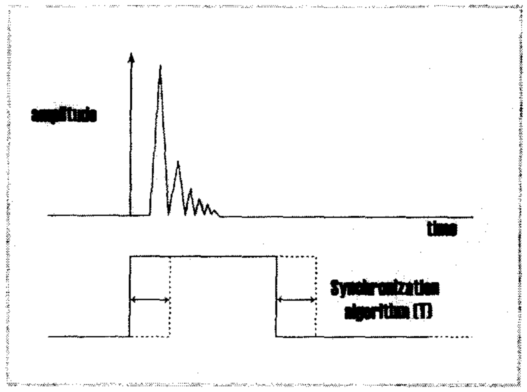

Figure 7: Synchronization for COFDM

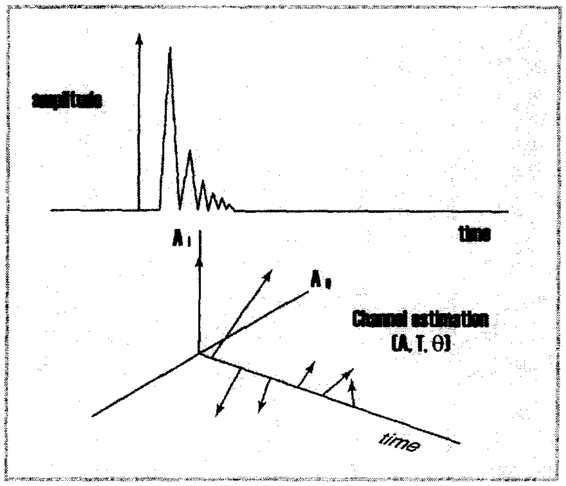

Figure 8: Synchronization for TDM and CDM

The first key characteristic is the use of *wideband multi-carrier modulation,* which, through proper coding, minimizes the effect of frequency selective fading. The digital information to be transmitted is split over several individual narrowband carriers which, in the case of the Eureka-147 DAB system, are equally spaced over a bandwidth of about 1.5 MHz. Each carrier thus operates at a low bit-rate, which implies that the corresponding symbol duration can be increased to the point where it is much larger than the delay spread of the channel. The symbol duration, however, is kept small relative to the coherence time of the channel so that Doppler effects are negligible. In order to achieve high spectral efficiency, Orthogonal Frequency Division Multiplexing (OFDM) is used as the multi-carrier modulation scheme. In OFDM, the modulated carriers form an *orthogonal set* (after proper time windowing in the receiver), due to the fact that their frequency spacing is the reciprocal of the useful symbol period. The carriers are thus independent of each other, even though their spectra (which are of sin x/x shape) overlap in the frequency domain. One further advantage of OFDM is that the modulation and demodulation processes can be implemented simply by means of an IFFT (Inverse Fast Fourier Transform) and FFT respectively. The modulation applied to each subcarrier is DQPSK (differentially encoded quadrature phase shift keying). It is associated with differential demodulation and soft decision outputs in the receiver.

4.2.2 Guard interval

The second key characteristic of COFDM is the use of a *guard interval* which is inserted at the transition between successive symbols to absorb the inter-symbol interference (ISI) created by multipath in the channel. The duration of this guard interval is usually selected so that it exceeds the maximum expected multipath delay spread of the channel. In the Eureka-147 DAB system, it is set to approximately 20% of the total symbol period. The receiver simply ignores the signal during the guard interval, since it is likely to be corrupted with inter-symbol interference (ISI) and, therefore, unreliable. Detection is made with the remaining 80% of the symbol called the useful symbol period, which is normally free of ISI and where the orthogonality of the subcarriers is preserved. No channel equalization is therefore required. The price to pay for this, however, is a reduction of about 20% in throughput. The presence of a guard interval in COFDM is the basis of one distinctive and very important feature of this system: *the possibility of using on-channel re-transmitters.*

4.2.3 Time & frequency interleaving

The third key feature of the COFDM scheme is the use of an *error correcting code* in combination with *interleaving* to combat fading in the mobile channel. Fades will always be present and when they occur, they may wipe out a number of contiguous subcarriers, causing erroneous bits in the receiver. To prevent this, the information bits are protected with a convolutional code. Prior to transmission, the error protected bits are interleaved both in time (over several symbols) and in frequency (over the wideband multi-carrier set). These two interleaving processes will ensure that most of the bursts of errors produced in the channel will be reduced to single random errors in the receiver after the de-interleaving processes have been applied. These random errors are then corrected by the convolutional decoder, implemented with a soft decision Viterbi decoder.

COFDM relies on both time diversity (interleaving of the data over several symbols) and frequency diversity (interleaving of the data over the wideband multi-carrier set) to overcome the time and frequency selectivity of the mobile channels. When the receiver is stationary, the time interleaving becomes ineffective, but the frequency diversity, provided by the wideband multi-carrier set, ensures that the system operates correctly. The fact that the channel fading is usually frequency selective (i.e., the channel coherence bandwidth is smaller than the COFDM signal bandwidth) provides for a major advantage over narrowband emissions.

Interleaving is done in the Eureka-147 DAB system by frequency interleaving over the entire 1.536 MHz channel bandwidth and time interleaving over a 384 ms span. In fact, both frequency and time interleaving are done through a single and straight forward interleaving mechanism. Similar mechanisms can easily be extrapolated for any other COFDM type modulation systems.

The COFDM principles used in the Eureka-147 DAB system are described in Figure 9.

4.2.4 Error control coding

Four main factors come into play in the selection of an error control coding scheme for a given application: the maximum residual bit error rate after decoding, the power and spectral efficiency of the code, and its decoding complexity. In broadcasting, the decoder must be capable of low cost implementation, since it is part of a mass consumer receiver. The code must also be spectrally efficient, since the spectrum available is often limited. Power is usually less of a concern, especially with digital transmission, where power levels required to provide adequate service are an order of magnitude less than the current AM and FM broadcast services. Depending on the trade-off made between these factors, different error control coding strategies can be chosen.

If the required decoded bit error probability is moderately low, i.e. 10^{-4} or greater, an error control scheme often used over fading channels is a convolutional code, combined with a channel bit interleaver. This is the scheme used in the Eureka-147 DAB system. It consists of a rate-compatible punctured convolutional code (RCPC) [17, 18]. The rate of the RCPC code can be adjusted by puncturing a constraint length 7, rate ¼ mother code. With a puncturing period of 8, coding rates between 8/9 and 8/32 can be achieved [19]. Five levels of protection for audio and eight levels of protection for data services are available. Maximum-likelihood decoding is done with the Viterbi algorithm. In the Eureka-147 DAB system, the audio source coding algorithm used is the MPEG-1 Layer 2. This source coding scheme has been shown to require, for two audio channels, a bit error rate at the input of the audio decoder ranging between 10^{-3} and 10^{-4}, depending on the nature of the audio materials [20]. So the use of a RCPC code is well matched to this particular source.

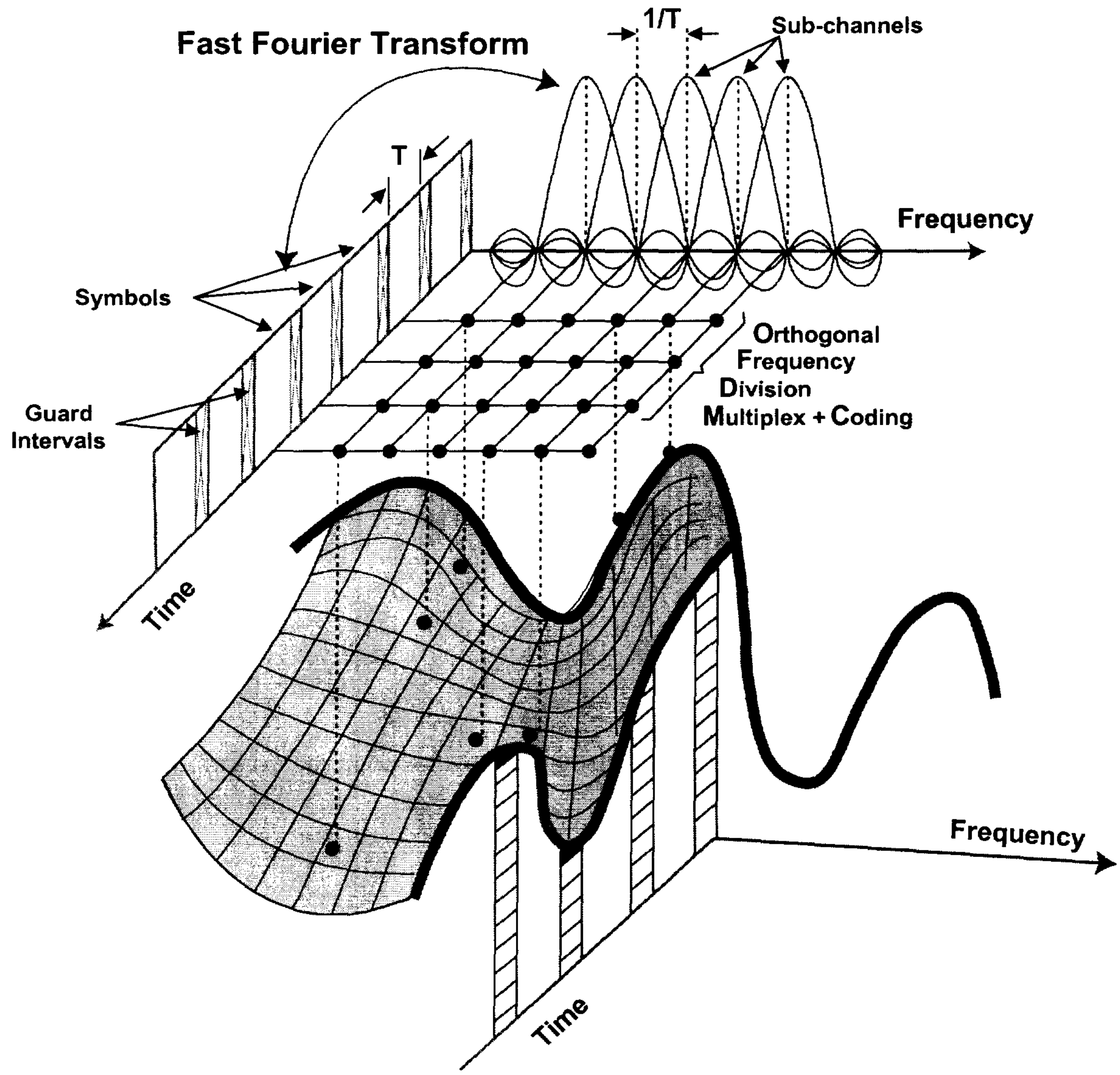

Figure 9: Illustration of COFDM demodulation from a frequency selective Rayleigh channel

If the required decoded bit error probability is 10^{-5} or less, then an alternative to the convolutional code when power or spectrum is limited is a concatenated code. In this scheme, an inner convolutional code is combined with an outer Reed-Solomon (RS) code as shown in Figure 10. The idea is that no matter how well the channel bit interleaver is designed, the inner convolutional code will occasionally make errors that will normally be bursty. It is the job of the outer RS code to correct these errors and RS codes are well-suited to correct those complex, bursty error patterns.

Figure 11 shows the performance of COFDM at L-band with a rate ½ RCPC code as well as with a rate ½ concatenated code in a Rayleigh fading channel. The vehicle speed is 50 km/h. Both curves are analytical lower bounds to the bit error rate [19, 21]. The curve for the convolutional code is about 0.5 dB lower than computer simulation results [22], so the bound is a tight one. The concatenated code consists of an outer RS (127,111) combined with a constraint length 7, rate 4/7

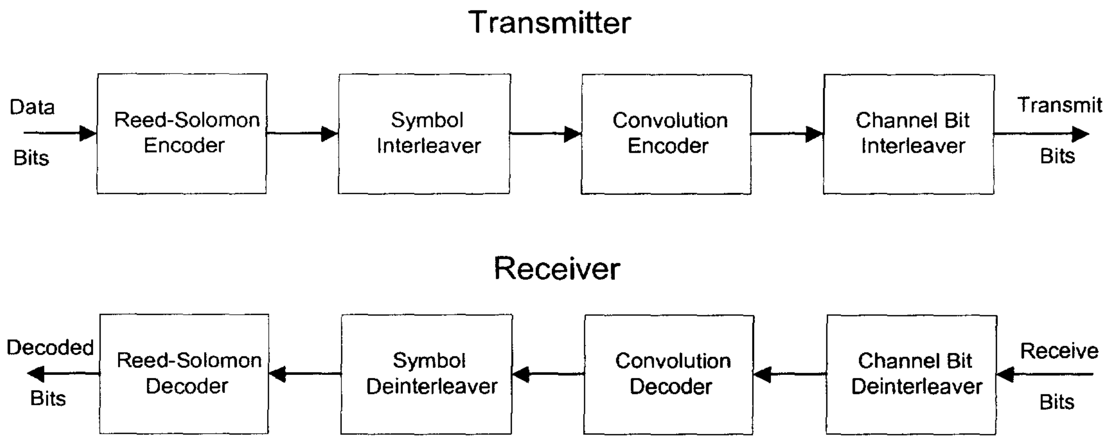

Figure 10: Block diagram of a concatenated Reed-Solomon/Convolutional code

RCPC code. The RS code has the capability of correcting up to $t = 8$ symbols having 7 bits. This particular code concatenation is given as an example and has not been optimized whatsoever.

For example, an alternative solution which was proposed in the original research work done on the Eureka-147 DAB system [13] was to use a CSRS(336,288) (cyclotomatically shortened Reed-Solomon) code instead of an RS as the outer code. The essential interest of the CSRS codes is that they do not require processing over the Galois field extension $GF(2^8)$, but only over GF(2). As a result, the implementation of the decoder is considerably simplified. Figure 11 shows that for bit error rates less than 10^{-3}, concatenation offers no significant advantage over the convolutional code. For bit error rates less than 10^{-5} however, the concatenated code is markedly superior. For instance, it requires about 5 dB less power than the convolutional code at a bit error rate of 10^{-7}. The price to pay is a somewhat more complex receiver.

4.2.5 Basic parameters

The main transmission parameters of the Eureka-147 DAB system are summarized in Table 3. The system was especially designed for operation in a multipath environment and over a wide range of operating frequencies from 100 MHz to 3 GHz. Four operating modes were implemented in the system, each mode being optimal for different segments of this frequency range. Important resulting parameters are the nominal separation distances between transmitters resulting from the extent of the guard interval that is possible for each transmission mode. These nominally correspond to the distance covered, at speed of light, over the extent of the guard interval duration in the case of a synchronous Single Frequency Network (SFN). The distances are halved in the case of the coverage extenders fed over-the-air since half of the guard interval duration would be used to bring the signal to the repeater. These values are very important in establishing the potential complexity of a SFN covering a given area.

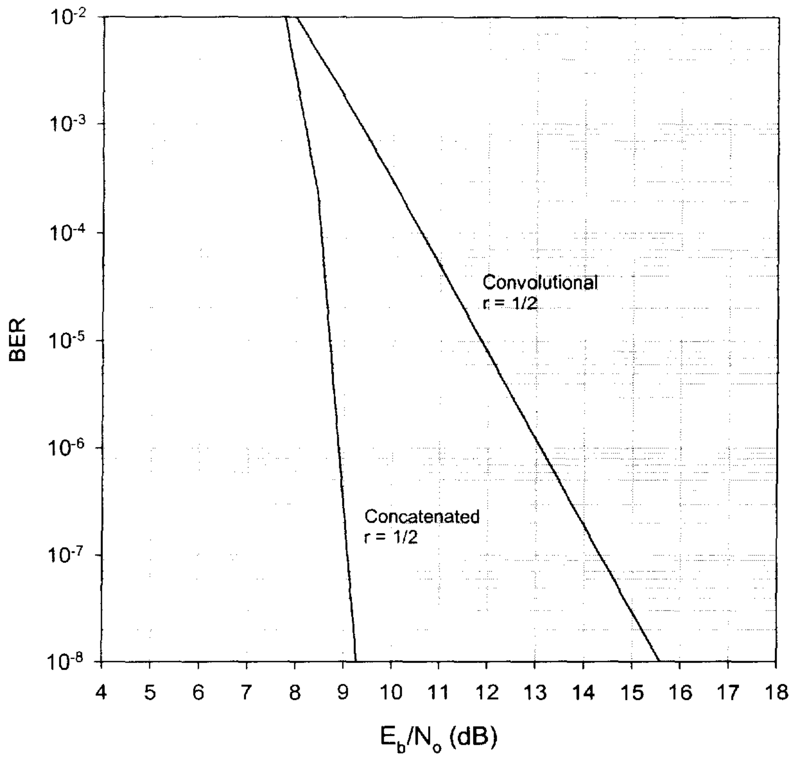

Figure 11: Performance of COFDM at L-band with rate ½ convolutional and concatenated codes in a Rayleigh fading channel (v = 50 km/h)

	Mode I	Mode IV	Mode II	Mode III
Frequency of operation (center of range)	375 MHz	750 MHz	1.5 GHz	3 GHz
Null symbol duration, T_{NULL}	1.297 ms	648 μs	324 μs	168 μs
Overall symbol duration, ($T_s = t_u + \Delta$)	1.246 ms	623 μs	312 μs	156 μs
Useful symbol duration, t_u	1 ms	500 μs	250 μs	125 μs
Guard interval duration, Δ	246 μs	123 μs	62 μs	31 μs
Number of radiated carriers, N	1 536	768	384	192
Nominal maximum transmitter separation for synchronized SFN	96 km	48 km	24 km	12 km
Nominal maximum repeater separation for RF pick-up coverage extenders	48 km	24 km	12 km	6 km

Table 3: Transmission parameters of the Eureka-147 DAB system

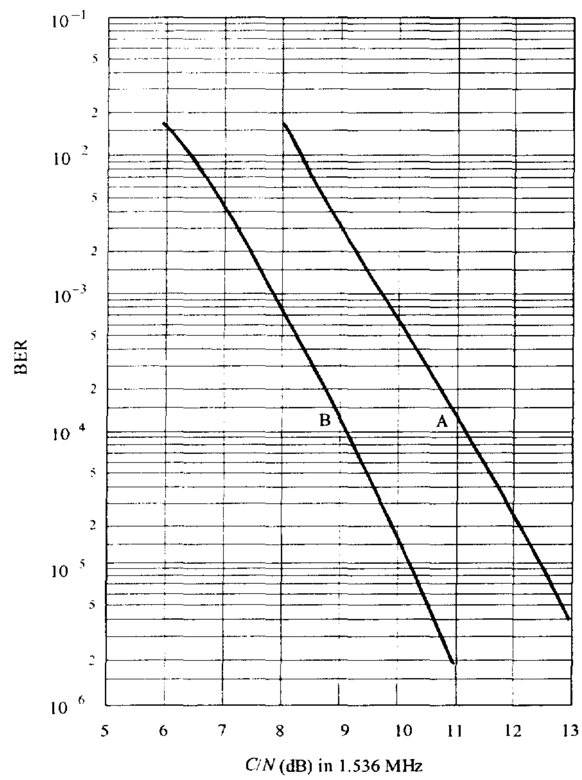

Figure 11: Measured performance of the Eureka-147 DAB system in terms of bit-error rate in a Rayleigh channel (Mode II at 1.5 GHz)

4.2.6 Minimum field strength requirement

The following Table 4 describes a typical link budget for the MMBS strawman system using the assumptions developed for the receiver in section 3.1 and using the performance of the Eureka-147 DAB system in a Rayleigh channel as depicted in Figure 11 for a ½ code rate.

This results in a minimum field strength of 41 dB(μV/m) for a MMBS channel of 1.5 MHz bandwidth. Comparing it to the 39 dB(μV/m) minimum field strength required for a DTV channel of 6 MHz in the UHF band, it can be concluded that MMBS would need some 8 dB more power per unit bandwidth at the receiving antenna to provide the service to the omni-directional mobile receivers.

4.2.7 Tradeoff between extent of guard interval and effects of Doppler spread

An intrinsic limitation of the mobile multipath channel is its time variability, which is a function of the speed of the vehicle. Typically, digital systems need to demodulate symbols over time invariant channels for reliable signal recovery. The length of the symbol is therefore limited by the time during which the channel is assumed to be constant. In the case of a differential demodulation, this time has to actually span two successive symbols. Since, in the case of COFDM, the symbol time can be stretched by spreading the information over a large number of orthogonal carriers, this channel time variability is an operating bound beyond which the performance of the system begins to be affected.

SYSTEM= EU-147 DAB		
Operating frequency	770	MHz
Channel bandwidth	1.500	MHz
Channel error protection	Convolutional (R= 1/2)	
Useful bit rate	1.200	Mbit/s
Useful symbol duration (Mode IV)	500.0	us
Guard interval (Mode IV)	125.0	us
Required C/N for BER= 10^-4 (Rayleigh channel)	11.2	dB
System and hardware implementation margin	0.8	dB
Interference allowance	2.0	dB (1)
Required minimum C/N at decoder	14.0	dB
Receiver Figure of merit		
Receiving antenna gain	0.0	dBi
Antenna noise temperature including man-made noise	146	K (2)
Antenna coupling and pre-selective filter losses	2.0	dB
Receiver noise figure	3.0	dB
Receiver figure of merit	-28.9	dB (K^-1)
Receiver input levels		
Minimum receiving antenna input power	-124.0	dBW
Minimum receiver LNA input power	-96.0	dBm
Minimum usable field strength		
Effective antenna aperture (Lambda^2/4*PI)	-19.2	dB (m^-2)
Minimum power-flux density	-104.8	dB/m^2
Minimum usable field field strength for 1.5 MHz block	41.0	dB(uV/m)

Notes:

(1) Allowance in the noise link budget for interference for 90% service availability resulting in 26.2 dB aggregate co-channel interference ratio between C and I medians for sigma= 5.5 dB (uncorrelated case) and 16.3 dB between C and I medians if C and I fades were fully correlated.

(2) Includes thermal noise from the surroundings (25% of antenna pattern), sky noise due to oxygen and water vapor (75% of antenna pattern) and industrial noise in suburban environment (based on ITU-R Rep. 285: suburban case; ITU-R Rep. 670: residential case).

Table 4: Link budget for the suggested MMBS system assuming the Eureka-147 DAB system as a reference

Extensive laboratory and field testing, using the Eureka-147 DAB system at 1.5 GHz, permitted characterization of the phenomenon as an increase in required Eb/No as a function of the vehicle speed. Figure 12 summarizes all these findings scaled for Mode IV at 770 MHz. These results can be considered as typical of any COFDM system using DQPSK modulation that uses a total symbol period of about 623 μsec. As can be seen, a large amount of data was collected from field measurements in addition to simulation and laboratory results, so that availability figures at 99% and about 80% could be deduced. All these measurement results were contributed to the ITU-R [23, 24].

By extrapolating from Figure 12, for a service availability of 90%, it can be found that a MMBS using a COFDM/DQPSK modulation with 500 μsec useful symbol period, the impact of a vehicle speed of 120 km/h would be an increase of about 1 dB in required Eb/No. A 3 dB increase would correspond to a vehicle speed of about 145 km/h. The effect of the Doppler spread on the system would be more pronounced for a service availability of 99% with an increase in Eb/No of some 10 dB at 120 km/h and 17 dB at 145 km/h. It can therefore be safely concluded that a MMBS system using COFDM/DQPSK modulation and a useful symbol period of 500 μsec would be sufficiently immune to the effects of channel Doppler spread for vehicle speeds of up to 120 km/h at 770 MHz.

There is a need to maximize the extent of the guard interval to facilitate the use of on-channel repeaters since the allowed distance between these repeaters is a direct function of this guard interval as explained in section 4.2.6. However, this guard interval has to be restricted to maintain the robustness of the system against the effect of Doppler spread since a reasonable ratio of 20% has to be preserved between the guard interval and the total symbol period. A larger ratio could be used but would result in an excessive reduction of the system capacity.

It is therefore concluded that the MMBS system strawman should operate with a useful symbol period of 500 μsec and a guard interval of 125 μsec resulting in a vehicle speed of more than 120 km/h and a on-channel repeater separation of 50 km for a synchronous SFN and 25 km for off-air pick-up repeaters.

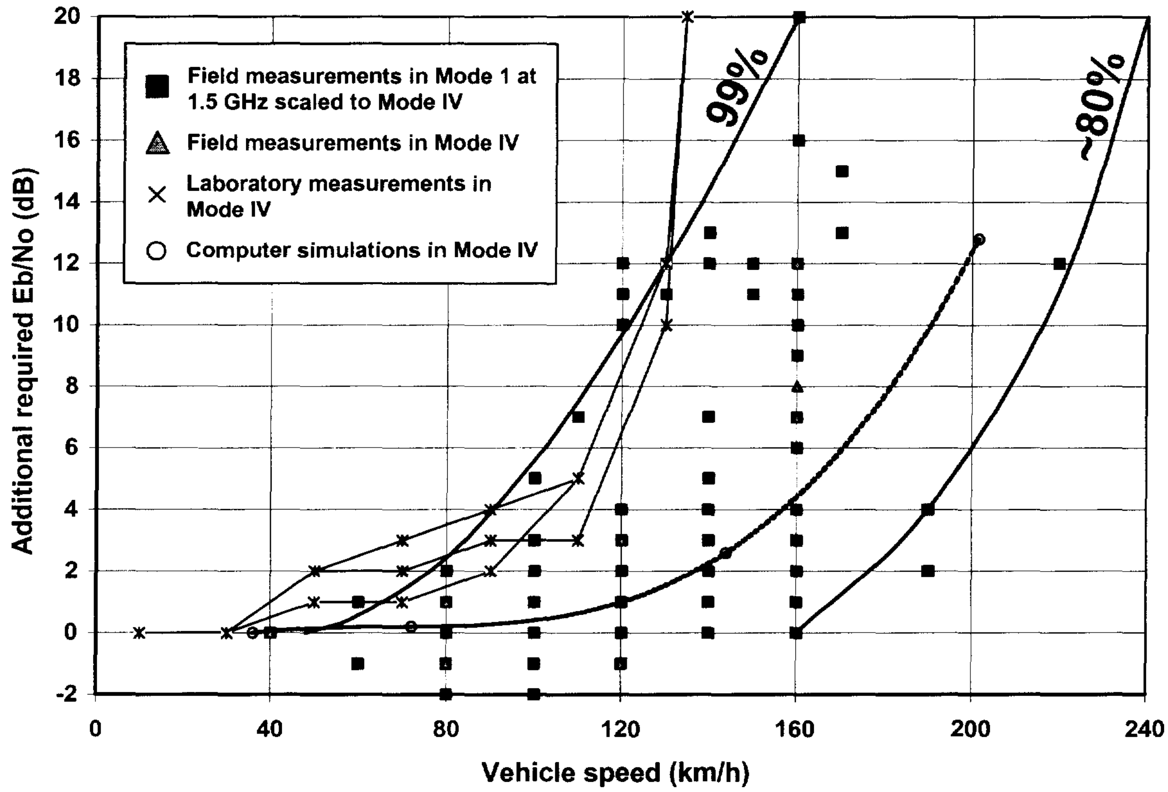

Figure 12: Doppler spread performance of Eureka-147 DAB in Mode IV (Tu=500usec) scaled at 770 MHz in urban and suburban environments

5. Audio service

5.1 Multichannel Audio: bit rates

There are a number of known algorithms that are capable of encoding multichannel audio programs at low bit rates. The most prominent ones are MPEG Layer II, MPEG Layer III, MPEG Layer AAC, Dolby AC-3 and Lucent PAC. Not all of them have been formally tested in the recent years. There is a scarcity of test results for multichannel audio codecs, the main reason being that very few testing facilities are equipped for 5.1 channels. The BBC and NHK conducted the most recent comparative tests in November 1996 for the ISO/IEC MPEG-2 standard committee [25]. These tests compared a